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A preventive maintenance model for leased equipment subject to internal degradation and external shock damage

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ABSTRACT

A periodic preventive maintenance modeling method is proposed for leased equipment with continuous internal degradation and stochastic external shock damage considered simultaneously, which can facilitate the equipment lessor to optimize the maintenance schedule for the same kind of equipment rented by different lessees. A novel interactive mechanism between the continuous internal degradation and the stochastic external shock damage is established on the hazard rate of the equipment with integrating the imperfect effect of maintenance. Two improvement factors are defined for the modeling of imperfect maintenance. The number of failures resulting from internal degradation and from external shocks are both mathematically deduced based on this interactive mechanism. The optimal preventive maintenance scheme is obtained by minimizing the cumulative maintenance cost throughout the lease period. Numerical example shows that the proposed preventive maintenance model not only can reflect the reliability status of the equipment but also can clearly distinguish between the impact from internal degradation and that from external shocks.

1. Introduction

PM (preventive maintenance) is an effective way to ensure the good condition of equipment. Currently, leasing equipment rather than owning equipment is becoming more and more popular. With the increasing complexity of equipment, there is a trend for the lessee to outsource the maintenance service because performing maintenance actions on this kind of equipment usually requires expensive tools and professional technicians. Therefore PM has become an important issue for the lessor. In order to fulfill the demands of the lessee, an effective PM schedule usually needs to be specified in the lease contract [1].

Throughout the years, the maintenance modeling has been widely studied [2], and in recent period, more and more efforts have been paid on the PM scheduling for leased equipment. Generally, there are two types of PM models for leased equipment. First is the periodic PM model [3–5]. In this model, PM is performed at some fixed time intervals, which means that the PM interval does not change within the whole lease period of the equipment. However, this model is different from the traditional periodic PM model because it assumes that PM is imperfect and it cannot restore the equipment to be as good as new. Second is the sequential PM model [6–9]. This model focuses on the imperfect effect of PM which inevitably leads to the increase of the failure frequency with the aging of equipment. A decreasing sequence for the PM interval is usually considered to keep the reliability of the equipment above a predetermined level. However, the continuous change of the PM interval not only may bring troubles to the scheduling management of the PM activities for the lessor, but also may disorganize the normal production rhythm for the lessee. In this sense, the sequential PM model is not as convenient and practical as the periodic PM model although it can ensure the reliability of the equipment. Anyhow, the common feature of these two models is that the lessor is in charge of the maintenance of the leased equipment. In such an instance, the lessee usually asks for compensation for the failures of the equipment which may bring huge production loss. Commonly, more frequent PM can decrease the failure frequency and then the penalty cost, but it also means the higher PM cost. Therefore, most of these models derive the optimal PM scheme by achieving a tradeoff between the penalty cost and the maintenance cost under leasing condition [3,6].

It is certain that the above PM models are playing great roles in improving equipment reliability, preventing equipment failures and reducing maintenance cost. However, more concern still needs to be paid on the operating convenience of the PM models under leasing condition. In reality, the equipment lessor usually rents the same kind of equipment to different lessees simultaneously. Assume these equipment, composed of the same components and subsystems, would experience a same degradation feature when they operated under the same ideal condition, which is defined as

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Notation

$h_i(t)$	internal hazard rate function within the ith PM cycle
H_i^I	hazard rate right before the ith PM resulting from internal degradation
H_i^E	hazard rate right before the ith PM resulting from external shock damage
H_i^0	hazard rate right after the $(i-1)$th PM
H_i	hazard rate right before the ith PM.
a_i	hazard rate decrease factor
b_i	hazard rate increase factor
μ	adjustment coefficient for hazard rate increase factor
T	PM interval
N^p	number of PMs within lease period
C^p	cumulative PM cost throughout lease period
C^c	cumulative minimal repair cost throughout lease period
C^{fp}	cumulative penalty cost throughout lease period
C^r	replacement cost
C^{pd}	cost for a single PM
C^{cd}	cost for a single minimal repair
C^{fpd}	cost for a single failure penalty
N_i^c	number of failures within the ith PM cycle
N_i^{sf}	number of failures within the ith PM cycle resulting from external shocks
N_i^s	number of shocks within the ith PM cycle
(β,η)	characteristic parameters for internal degradation
(λ,θ,γ)	characteristic parameters for external shocks
H_{ij}	hazard rate after the jth external shock within the ith PM cycle
W_{ij}	increment value of hazard rate resulting from the jth external shock within the ith PM cycle
$G^{(j)}(X)$	j-fold Stieltje convolution of $G(X)$
$G^*(\theta)$	Laplace–Stieltjes transform of $G(X)$
t_j	arrival time of the jth external shock
ξ	a constant coefficient for the calculation of $h_1(t_j)$
n^p	failure threshold for compensation
σ	failure threshold factor

the normal degradation process. However in practice, these equipment usually run in different environments and are subjected to different shock damages. In order to master not only the common normal degradation feature of these equipment but also their individual damage characteristic, the lessor requires a more efficient PM model which can distinguish between the hazard from internal degradation and that from external shock damage. In reality, a great number of components and systems are subjected to interactive failures of degradation processes and random shocks. For example, although the same type of planes flying on different routes usually has the same normal degradation feature, their landing times may be different. These different numbers of shocks can also cause different damages. Another example, a battery is gradually weakened by usage and finally turns out to be useless when the substances are exhaustive. At the same time, overheating or overvoltage can also cause the damage of the battery. Besides, for an electronic component, failures cannot only result from wear-out process, which usually happens when it has run for many cycles, but also the overloading stress to the system caused by random voltage spikes.

In fact, more attention is being paid on the fusion of internal degradation and external shock damage in order to describe the degradation mechanism of equipment more accurately. Rafiee [10] analyzes the system reliability subject to s-dependent competing risks of internal degradation and external shocks. Caballé [11] divides failures into two dependent causes: the degradation failure occurs when the deterioration level exceeds a predetermined value, and the sudden shocks provoke the total breakdown of the system. Iberraken [12] developes a competing risk model including both degradation and shock process by applying the Weibull–Markov approach and state probability assessment. Lin [13] extends a multi-state model for component reliability assessment by including semi-Markov and random shock process. The transition rate of the reliability model is decided by the number of cumulative shocks. Ruiz [14] analyses the behavior of a device that is exposed to internal failures and external shocks. The internal performance of the device occupies several degradation levels, and each level is partitioned into different damage states. When external shocks occur, the device undergoes external damage which can occupy one or more degradation levels. Refs. [15–18] are the other similar researches combing internal degradation and external shock damage. On the whole, the focus of these existed efforts is to reveal the mechanism on how the external shocks affect the internal degradation. However, they pay little attention on how the internal degradation affects the external shock damage. In fact, there exists an interactive relationship between the internal degradation and the external shock damage. The velocity of the internal degradation increases with the accumulation of the external shock damage, while the failure probability resulting from the external shocks increases too with the accumulation of internal degradation. Obviously, this interactive relationship is rarely considered in the existed efforts.

In this paper, a new PM model for leased equipment is proposed with integrating this kind of interactive relationship between the continuous internal degradation and the random external shock damage. It is assumed that PM can decrease the cumulative hazard of the equipment but not to zero, and consequently the internal degradation velocity of the equipment increases after each PM because of the increasing salvage hazard, which in return has great impact on the failure probability resulting from the external shocks. A modified two improvement factors method is introduced for imperfect PM modeling to reflect the correlation between the internal degradation and the external shock damage. The optimal PM scheme is obtained by achieving a tradeoff between the penalty cost and the maintenance cost.

The remainder of this paper is constructed as follows. Section 2 gives an imperfect maintenance model with the interactive relationship considered. The overall PM model is built up in Section 3. Finally, Section 4 illustrates a numerical example to show the availability of the proposed PM model.

2. Imperfect maintenance modeling

Imperfect maintenance study indicates a significant breakthrough in reliability and maintenance theory. In reality, PM is usually imperfect and it cannot restore the status of equipment to be as good as new, but younger [19,20]. Wang [21] summarizes eight different kinds of modeling methods for imperfect PM. One of them is the improvement factor method [22–26]. This method is practical in engineering because the maintenance decision is based on the system hazard rate or other reliability indexes. In this paper, it is adopted for the imperfect PM modeling of the leased equipment. However, the modeling detail is different from the traditional one because the internal degradation and the external